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DRAG MEASUREMENT IN A LOW DENSITY GAS STREAM

W. Stephenson and D. Whitfield

ARO, Inc.

May 1970

AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

Two methods of measuring the drag of bodies in a low density gas stream are described. The supersonic stream had a mean free path as great as 4 cm, and the drag forces were small. A drag balance was adapted from an electrical analytical balance to measure forces up to 70 dynes with less than 1-percent error. With this balance, the drag of spheres was measured for the Knudsen number range from 1.0 to 5. The freedrop trajectory method yielded drag coefficients in the range of Knudsen numbers from 2.5 to 30. These tests demonstrated the feasibility of making accurate drag measurements under the free-molecule conditions that can be generated by exhausting a gas into a cryogenically pumped vacuum chamber.

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NOMENCLATURE

A Cross section area of model

a Sound speed $(\sqrt{\gamma RT})$

C_D	Drag coefficient (D/qA)
D	Drag force
d	Model diameter
E	Modulus of elasticity
g	Acceleration of gravity
I	Section moment of inertia (beam)
Kn	Knudsen number (λ/d)
l	Length
M	Mach number (u/a)
q	Dynamic pressure ($\rho u^2/2$)
R	Gas constant ($P/\rho T$)
S	Speed ratio ($u/\sqrt{2RT}$)
T	Temperature
u	Stream speed
W	Weight of model
γ	Ratio of specific heats
δ	Deflection of beam
θ	Slope of trajectory
λ	Mean free path
μ	Coefficient of viscosity
ρ	Density
ω	Viscosity-temperature exponent

SUBSCRIPTS

m	Model
o	Standard temperature and pressure
T	Stagnation state
W	Model wall
∞	Undisturbed stream

SECTION I
INTRODUCTION

An extremely low density supersonic gas stream can be generated in a vacuum chamber when cryogenic surfaces are available to provide large volumetric pumping rates. The Aerospace Research Chamber (8V), shown in Fig. 1 (Appendix), has been adapted to gas dynamic testing by the installation of supersonic nozzles and cryogenic surfaces that are supplied by 8-kw refrigeration at 20°K. If sensitive enough measuring techniques can be devised, the aerodynamic forces on bodies can be determined through the transitional flow regime from the continuum to the free-molecule state.

A requirement for the determination of the drag of spherical satellites led to planning a test program for measuring the drag of spheres through the transition regime (Knudsen numbers–ratio of mean free path to sphere diameter–from about unity to 50). Nitrogen was the desired test gas, and a maximum stagnation temperature of 900°K was required.

Of the methods of measuring the small drag forces, a modified electrical analytical balance and the freedrop method appeared most feasible. The manufacturer's specifications and some preliminary experiments had indicated that the balance would meet the requirements over at least part of the operating range. A low density nozzle usually has an upper limit of from 2- to 4-cm mean free path, and therefore the higher Knudsen numbers required small spheres of a millimeter or smaller diameter. The freedrop method therefore appeared most practical for Knudsen numbers greater than 5.

SECTION II
GENERAL CONSIDERATIONS AND FEASIBILITY

In the design of the experiment for low density drag determination, the relation between drag force and stream mean free path must be expressed. The definition of drag coefficient gives:

$$D/C_DA = \frac{\rho}{2} u^2$$

The mean free path in terms of a standard, λ_o, is given by

$$\lambda = \lambda_o \frac{\mu}{\mu_o} \frac{\rho_o}{\rho} \left(\frac{T_o}{T}\right)^{1/2}$$

or assuming a viscosity-temperature exponent, ω,

$$\rho = \rho_o \frac{\lambda_o}{\lambda} \left(\frac{T}{T_o}\right)^{\omega - 1/2}$$

From the energy equation for flow through a nozzle:

$$u^2 = a_T{}^2 \frac{M^2}{1 + \frac{\gamma - 1}{2} M^2} = \frac{\gamma R T_T M^2}{1 + \frac{\gamma - 1}{2} M^2}$$

and

$$\frac{T}{T_T} = \frac{1}{1 + \frac{\gamma - 1}{2} M^2}$$

Then the dynamic pressure is, in terms of the mean free path,

$$\frac{D}{C_D A} = \frac{\rho_o}{2} \frac{\lambda_o}{T^{\omega - ½}} \frac{\gamma M^2 R (T_T)^{\omega + ½}}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{w + ½}} \frac{1}{\lambda}$$

For nitrogen:

$$\rho_o = 1.25 \times 10^{-3} \text{ cm/cc}, \; T_o = 273°\text{K}, \; \lambda_o = 6.8 \times 10^{-6} \text{ cm}$$

$$R = 2.97 \times 10^6 \frac{(\text{cm/sec})^2}{°\text{K}}, \; \gamma = 1.4$$

and ω is assumed to be 0.7. These give

$$\frac{D}{C_D A} = 5.76 \frac{M^2}{(1 + 0.2M^2)^{1.2}} \frac{T_T{}^{1.2}}{\lambda}$$

Another method of generating a hypersonic stream is by the free-jet expansion from a sonic orifice. In this case, the flow speed approaches the limit

$$u = \left(\frac{2}{\gamma - 1}\right)^{½} a_T$$

and the static temperature may be assumed to reach a translational freezing limit of 10°K. Then

$$\frac{D}{C_D A} = 4.55 \times 10^{-2} \frac{T_T}{\lambda}$$

These relations are shown in Fig. 2. Figure 3 shows free-molecule drag coefficients for cones and spheres; C_D is about 2 for spheres. Therefore a sphere with a cross section of 0.5 cm^2 would have a drag force equal to the ordinate of Fig. 2. Since this force in dynes is practically the weight of the same mass in milligrams, an idea of balance requirements can be obtained. A balance which has a weighing capacity from about 1.0 to 200 mg would cover the Knudsen number range from unity to about 10 for a 1-cm model.

If the experimental facility is limited to nozzle flows, mean free paths cannot be expected to exceed 3 or 4 cm. Therefore, small diameter models must be used to reach Knudsen numbers greater than about 5. The support was thought to introduce too much interference for models less than 5-mm diameter, and a freedrop procedure appeared more suitable. If the model is dropped through a uniform stream, the downstream acceleration will be practically constant, and the trajectory will be inclined to the vertical at the angle $\theta = \tan^{-1}$ D/W. In terms of the experimental parameters,

$$\tan\theta = \frac{C_D\, A\, \rho\, u^2}{2(\frac{\pi}{6} d^3)\, \rho_m\, g} = \frac{3}{2}\, C_D\, \frac{q}{\rho_m d g}$$

The dynamic pressure, q, is related to mean free path, λ, by

$$q = \text{const}/\lambda$$

for fixed Mach number and total temperature. As an example, consider a Mach number 7.0 flow at a total temperature of 800°K. Let $C_D = 2$ and $\rho_m = 2.7$ gm/cc (aluminum).

$$q = 47.2/\lambda$$
$$\tan\theta = 0.0535/\lambda d$$

If 0.1 is taken as a value of tan θ, which can be read from a photograph with reasonable accuracy,

$$d = 0.535/\lambda$$

which gives the following for diameters and Knudsen numbers:

λ, cm	d, cm	Kn = λ/d
1	0.54	1.8
2	0.27	7
3	0.18	17
4	0.13	31

Smaller diameters would provide larger Knudsen numbers and larger tan θ. The lower practical limit in size is determined by the photographic quality.

SECTION III
DRAG BALANCE ADAPTATION

3.1 DESIGN

A commercially available electromagnetic analytic balance, designed for vacuum operation, appeared to be adaptable to the measurement of drag forces of the required magnitude. Full-scale ranges from 1.0 to 200 mg can be selected, and a resolution of a microgram can be readily obtained. The balance design is such that a maximum weight of 2.5 gm limits the addition of components to the beam. The beam of the balance is connected to a torque motor, which is similar to a meter movement with a flexure pivot. A servoamplifier, controlled by a vane on the beam that interrupts light to a photocell, supplies a current to the torque motor to null the beam displacement. This current is used for fine zeroing and for providing the signal proportional to weight in the pan.

The modifications of the analytic balance to a drag balance were based on several considerations: (1) the drag force would act horizontally; therefore, a rigid tube bent to an L-shape was added to the beam, (2) additional vibration damping was required because of the model support dynamic characteristics, (3) a remote method of weighting the balance for in-place calibration was desirable, and (4) the environment, with close proximity to cryogenic surfaces, made heaters necessary for stability. Figures 4, 5, and 6 show the configuration of the drag balance that was arrived at after development. The basic balance beam is shown with its two loops for the weight pan and counterweights. Cemented near the middle of the beam is the model support made of 0.8-mm OD, 0.1-mm wall, 303 stainless steel tubing. A finger is fastened to the forward end of the beam to hold the calibration ring weight when it is lowered by retraction of the ramp block. This ramp is moved by a lever operated by a cam driven by a clock motor. The weight of the calibrating ring was adjusted to give the same reading as 50 mg in the pan.

Figure 4 shows the method of increasing the damping of the system by adding an extension of aluminum wire with a 1.0-cm-diam aluminum foil vane which moves between the poles of a permanent magnet. The magnet had a nominal field of 2.2 kilogauss. Pole faces were added to reduce the diameter from 4 to 1.25 cm and the gap from 1.9 to 0.25 cm, which increased the maximum flux to about 6 kilogauss. Figure 7 is a copy of the balance output on the bench without the eddy current damping magnet and with it in place. The four filter positions on the readout unit are indicated. Position 3, which gave about ± 10-μg oscillation, was used during most of the experimental data runs.

When the balance was inside the vacuum chamber, surrounded by liquid-nitrogen-cooled walls, its reading was observed to drift steadily at about 1 mg/min. After the balance was retracted from the chamber and returned to room temperature, the drift was in the opposite direction. Heat loss was estimated at about 75 w in the cold environment. The temperature effect was eliminated by adding three small heaters and thermostats to the balance chassis and structural members.

The drag is measured in terms of weight in the pan, which is removed for testing. The ratio of drag to weight is then the same as the ratio of the horizontal distance from the beam pivot to the pan loop to the vertical distance from the pivot to the model. This ratio was 0.3425 and was determined by using a surveying theodolite to observe the balance mounted on the table of a milling machine. Therefore, a balance reading of 200 mg (full scale) would correspond to a drag force of about 70 dynes. On the ordinate axis of Fig. 2, this would be $D/C_D A$ = 107 dyne/cm^2 for a 0.64-cm model with a drag coefficient of 2.

A possible source of error might result from the deflection of the model support under drag loads. The deflection for a drag load, D, is $\delta = D\ell^3/3EI$, and the moment caused by the shift in model weight is $W\delta$. Since the moment about the pivot caused by drag is $D \times \ell$, then the error in drag is given by

$$\epsilon_{D|} = \frac{W\delta}{D\ell} = \frac{W\ell^2}{3EI}$$

For the weight and dimensions of the present configuration, this error is only 0.007 percent and therefore negligible.

3.2 OPERATION

In normal operation the balance is zeroed mechanically and electrically, and the sensitivity is adjusted by adding a National Bureau of Standards (NBS) class M calibrating weight to the pan. This weight corresponds to the midrange of the scale being used, 50 mg for the 100-mg range usually used. Mechanical zeroing consists of balancing the beam approximately by means of weights made of lengths of copper wire hung in the counterweight loop. Finer adjustment can be made by rotating one end of the flexure pivot. The final zero is obtained electrically. The calibrations below were made with NBS standard weights (accurate to 0.005 mg) in the pan:

NBS Standard Weight, mg	Balance Reading 7/24/69	8/4/69	8/4/69 (0.5-deg Tilt)
0	0	0	0
10	10.03	10.00	10.01
20	20.08	19.97	19.99
30	30.13	29.98	29.97
50	50.00	49.90	49.93
60	60.02	59.93	59.96
70	70.18	69.93	69.95
80	80.16	79.94	79.98
100	100.04	99.93	100.03

All these results were within 0.5 percent, most within 0.1 percent, and therefore considered adequate for the measurements required. The measurements in the last column were made to investigate the effect of tilting the balance half a degree, then rezeroing electrically. There was a suspicion that the large null current might affect the linearity of the calibration; however, it apparently did not deteriorate measurably. The reason for this investigation was that the balance was to be calibrated outside the main chamber in an airlock and then inserted on guide rails through a valve. In this process, it is practically impossible to maintain the balance level. With the 6.4-mm-diam aluminum sphere model, a weight reading change of 20 mg per degree of rotation will result.

The calibration ring (Fig. 4) was designed as a substitute for the accurate weight placed in the pan in order that the calibration could be made remotely. This ring was adjusted to give the same balance reading as a 50-mg weight in the pan.

The readout of weight is by means of a precision helical potentiometer in conjunction with a strip chart recorder. The potentiometer is calibrated to read a fraction of the selected mass range to four figures, and the strip chart is usually spanned to 1/100 of full range. In the present application, the strip chart was used only as a null indicator, and the forces were read on the mass fraction potentiometer.

3.3 AEROSPACE RESEARCH CHAMBER (8V) INSTALLATION

The chamber shown in Fig. 1 was adapted to drag measurement by the addition of an antechamber, valve, and a rail system attached to the existing x-z scanner mechanism (Fig. 8). This permits placing the model on the balance in the antechamber, calibrating the balance, and then transferring the balance carriage onto the rails mounted on the scanner. The scanner mechanism can then position the model at the axis of the nozzle. Also, it can locate the pitot tube in the same position for nozzle flow calibration.

A cryogenically cooled windshield, attached to the rails, was supplied with 20°K helium to minimize the support interference by condensing the stream behind the model (Fig. 6). The shield was inclined 45 deg to the stream and slotted so that the model support would pass through it.

It was found that large zero shifts resulted from movement of the balance into position, and a means of rezeroing the balance was necessary. A rail tilting mechanism made it possible to rotate the rails remotely at about 0.3 deg/min. In terms of weight in the pan, this amounts to 5 mg/min for the 0.64-cm sphere model. In practice, the testing program was greatly expedited because very precise balancing with counterweights was not necessary.

There are two auxiliary measurements that must be made if the model drag is to be determined and correlated: (1) the model temperature and (2) the support effect or tare drag. The temperature is measured for a duplicate of the drag model which is supported on thermocouple leads 5 to 10 diameters away to avoid interference but close enough to have the same temperature history. To make the tare drag determination, the duplicate model is located about a millimeter ahead of the drag model support from which the drag model has been removed. The support drag is then subtracted from the total measured drag.

SECTION IV
FREEDROP METHOD

The free-fall technique was devised to provide drag data for spheres in the Knudsen number range from 5 to 100. The lower limit of model size for the drag balance is not limited by measurement accuracy but by the fact that the tare drag force becomes a large fraction of the total drag. The model support is 0.75 mm in diameter, and sphere models less than about 5 mm would be difficult to position accurately enough for reliable tare measurements. The desired range of sphere diameters for the drop experiments was from 0.075 to 3 mm. A simple dropping mechanism (Fig. 9) was built, which consisted of a shaft that rotates 180 deg when the relay is energized. The shaft is drilled halfway through to provide recesses for the spheres. The mechanism is loaded in the antechamber and inserted similarly to the balance. A stroboscopic light (Fig. 10) illuminates the sphere as well as the scale and a plumb line in the field of view of a camera. The temperature of the sphere is assumed the same as the drop mechanism temperature, which is measured by a thermocouple on the chassis. Since the dropper is in the chamber only a short time, temperature changes are small.

The primary sources of error in determining the drag from free fall are (1) nonuniformity of the stream through which the trajectory passes, (2) resolution of the image on the film, and (3) variation of strobe light source frequency stability. These are minimized by curve fitting the trajectory and determining the slope at the centerline. The film reading was done on a special reader used for ballistic range data reduction. The data reduction procedures and accuracy are discussed in detail in Ref. 1.

SECTION V
SPHERE DRAG MEASUREMENTS

Figures 11 and 12 show the characteristics of the test stream where the drag measurements were made. The nozzle was designed for a Mach number of 6.0 at the exit at 1.0 torr supply pressure and 1000°K stagnation temperature. The Mach number and mean free path continued to increase downstream of the exit plane. The model on the balance was located about 25 cm downstream of the exit, and the drop trajectories extended from about 19 cm, where the launcher was located, to 35 cm for the smallest spheres. Mean free paths ranged from 1.0 to 4.0 cm. The Reynolds number regime extended from 0.3 to 10. Nitrogen was the test gas.

Figure 13 shows the drag of a 6.4-mm sphere as the supply pressure, P_{T_1}, is varied from 0.50 to 4.0 torr. Pressures less than 1.0 torr produce a merged boundary layer in the nozzle and invalid drag data. From the nozzle flow calibration (Figs. 11 and 12) the drag is reduced to coefficient form and plotted against Knudsen number in Fig. 14. The model wall temperature is also shown, as it varied during the two runs. The random scatter in C_D is about ±1 percent, which is probably mainly repeatability in the nozzle flow calibration. Most of the difference between the two test runs appears to be the result of model temperature.

Figure 15 is a print from one of the freedrop films showing the trajectories of 3.05- and 1.52-mm-diam spheres. The flash speed was 120/sec with about 40-μsec duration. The data reduction required determining the second derivative of the horizontal displacement from points along the trajectory. A second-order curve was obtained by a least-squares fit to the points read from a film reader (x versus time). The scatter in the data was about ±10 percent, as shown in Fig. 16. Several things contribute to this random error: (1) ability to read the film accurately, particularly for the small (0.76-mm) spheres, (2) the trajectories may have been displaced laterally off axis, (3) variation of the strobe flash frequency, and (4) uncertainty in the nozzle flow calibration. Only 6 to 12 points were used in the curve fits.

SECTION VI
CONCLUSIONS

This preliminary experimental study demonstrated the feasibility of making drag measurements on bodies in the free-molecule regime and the transition toward continuum gas dynamic conditions. Two methods proved to be practical: (1) use of an analytical balance modified for the purpose and (2) stroboscopic photography of the free-fall trajectory.

6.1 DRAG BALANCE

The Knudsen number range in these experiments was from about 1 to 5. These limits, however, were not determined by the balance but by the characteristics of the stream generated by the low density nozzle. The lower limit could be extended to a Knudsen number of 0.5 by increasing the supply pressure to 10 torr, although the run time would be short. If the stagnation temperature were reduced from 800 to 300°K, Knudsen number would be about 0.2 for maximum balance drag with the 0.6-mm-diam sphere.

The upper limit of Knudsen number was determined by the merging of the nozzle boundary layer. A hypersonic flow generated by a free-jet expansion would yield much greater mean free paths. The balance will be accurate at drags one-tenth of those measured, and therefore drag at a Knudsen number of at least 50 could be obtained.

6.2 FREEDROP METHOD

As pointed out in the previous section, the balance can measure drag at a very large Knudsen number. However, the flow must be generated by a free-jet expansion rather than inside a supersonic nozzle, where the boundary layer limits the degree of rarefaction. The free-jet flow sacrifices Mach number, since it is inherently hypersonic, so that one is forced to test small models when Mach number must be retained as a simulation parameter. Therefore, to avoid a major redesign of the support to accommodate small models to the balance, the freedrop procedure was selected as an expedient.

The ±10-percent random deviation of drag data from the freedrop data analysis is attributed to film reading problems and an insufficient number of points along the trajectory for curve fitting. By using the same data points to calculate the gravitational acceleration, one finds occasional deviations as great as ±10 percent from g. This may result from variations in strobe light frequency as well as film reading.

A significant improvement in drag measurement could be made by using photographic techniques developed for the von Kármán Facility low density tunnel. Strobe flash rates are from 500 to 2000/sec, which would increase the number of position points by a factor of 10. Since only 6 to 12 points were obtained for the present data, the random variation of drag data would be significantly reduced.

REFERENCE

1. Whitfield, D. and Stephenson, W. "Sphere Drag in the Free Molecule and Transitional Flow Regimes." AEDC-TR-70-32, April 1970.

APPENDIX
ILLUSTRATIONS

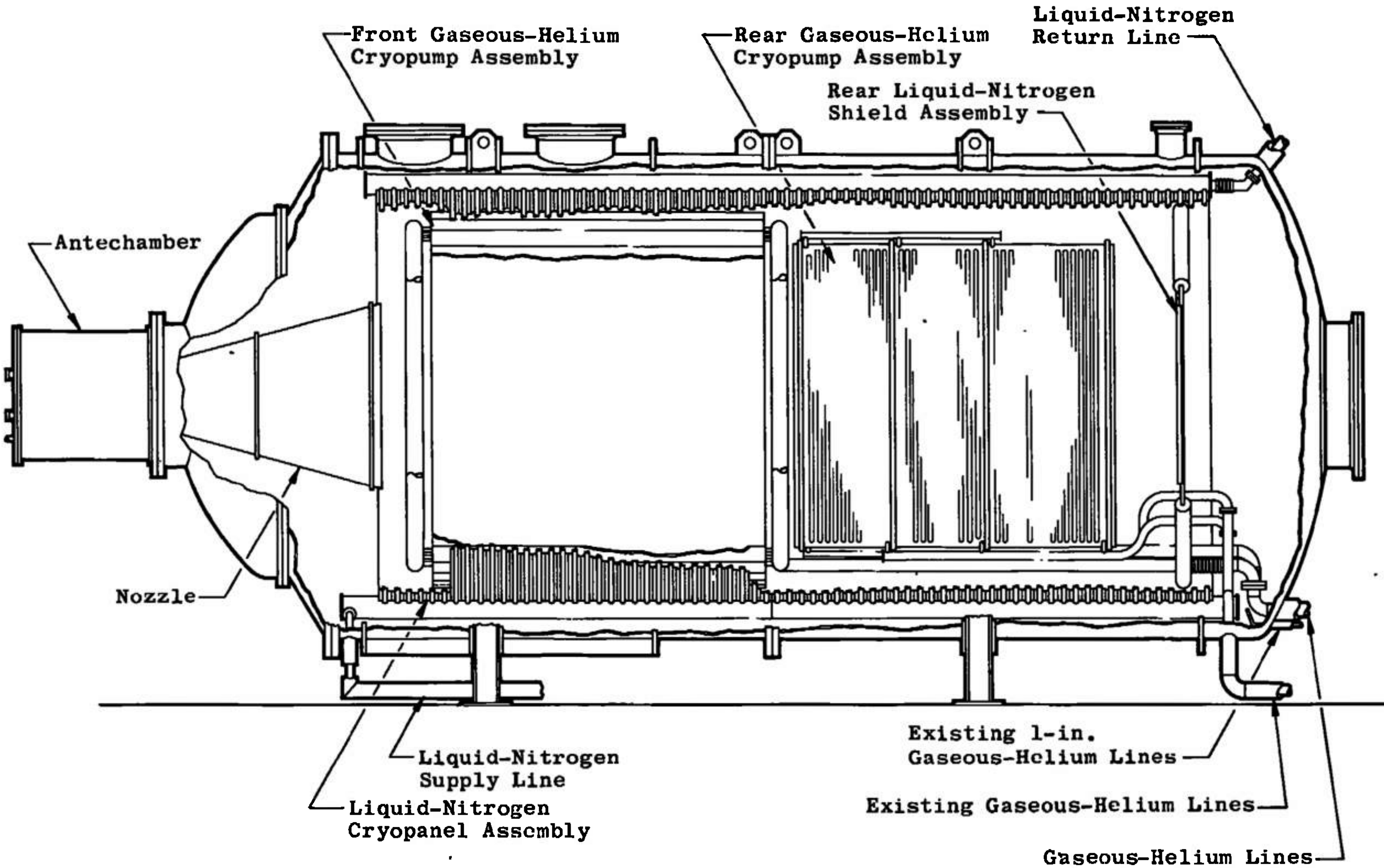


Fig. 1 Aerospace Research Chamber (8V)

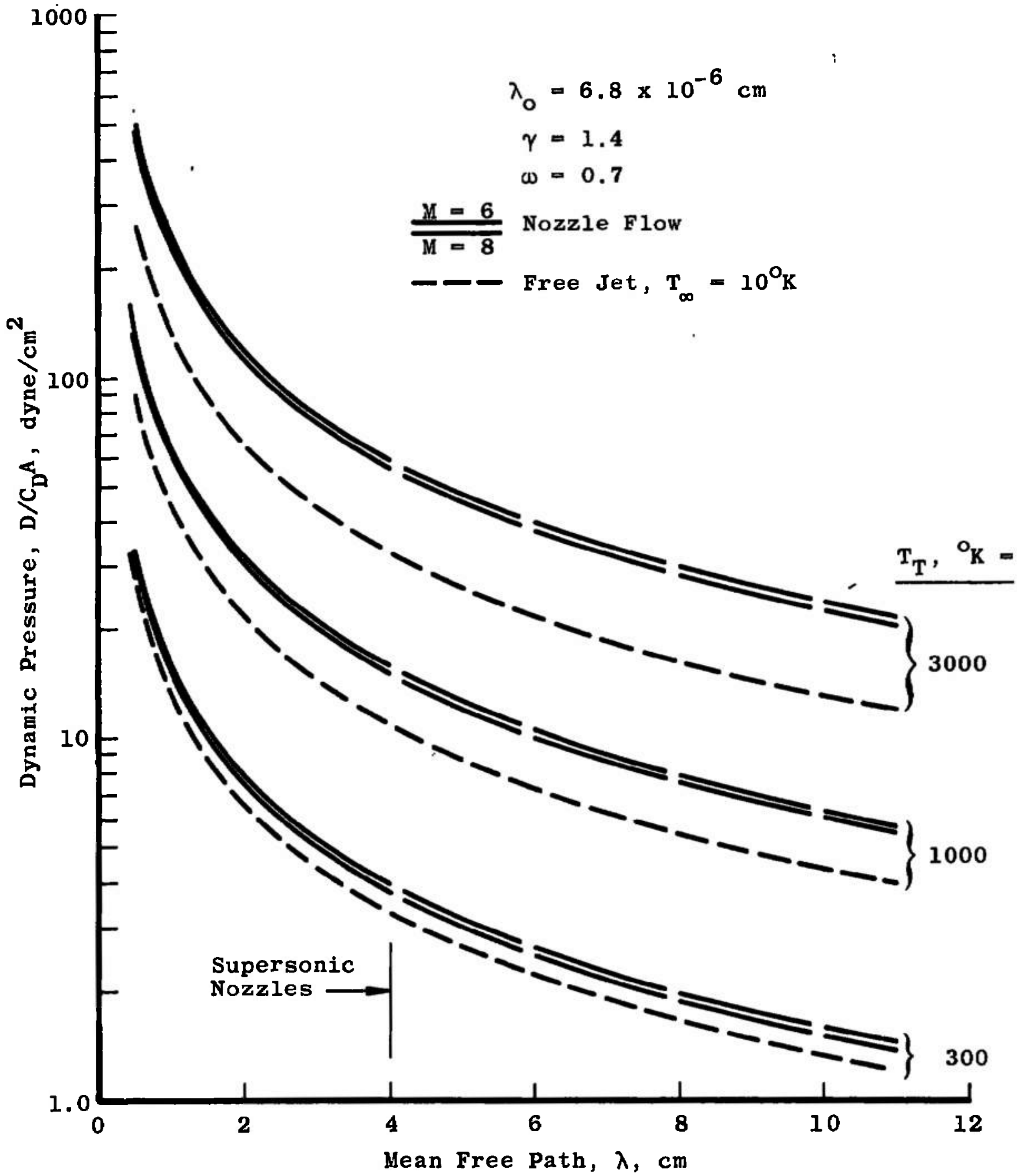


Fig. 2 Dynamic Pressure versus Mean Free Path

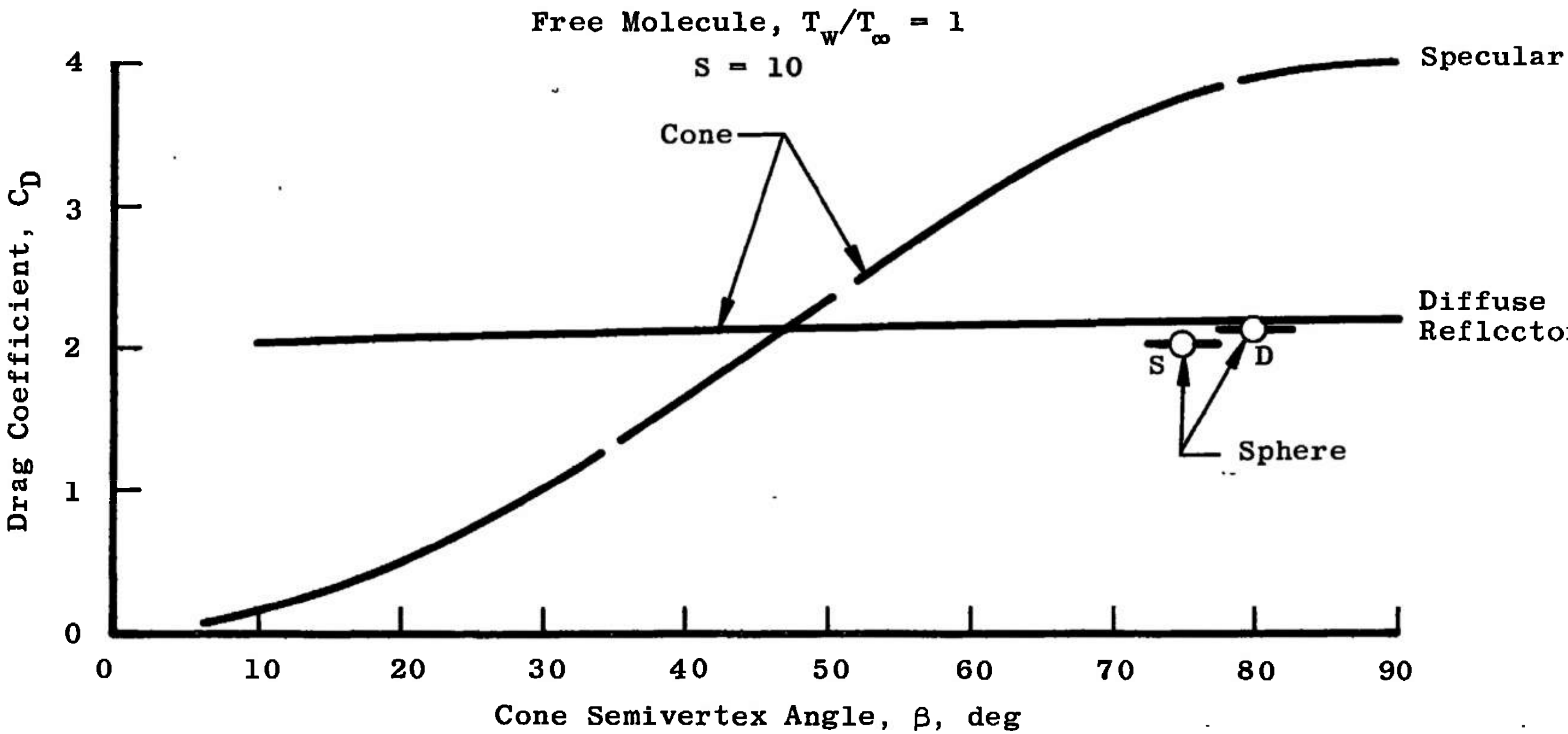


Fig. 3 Free-Molecule Drag Coefficients of Cones and Spheres

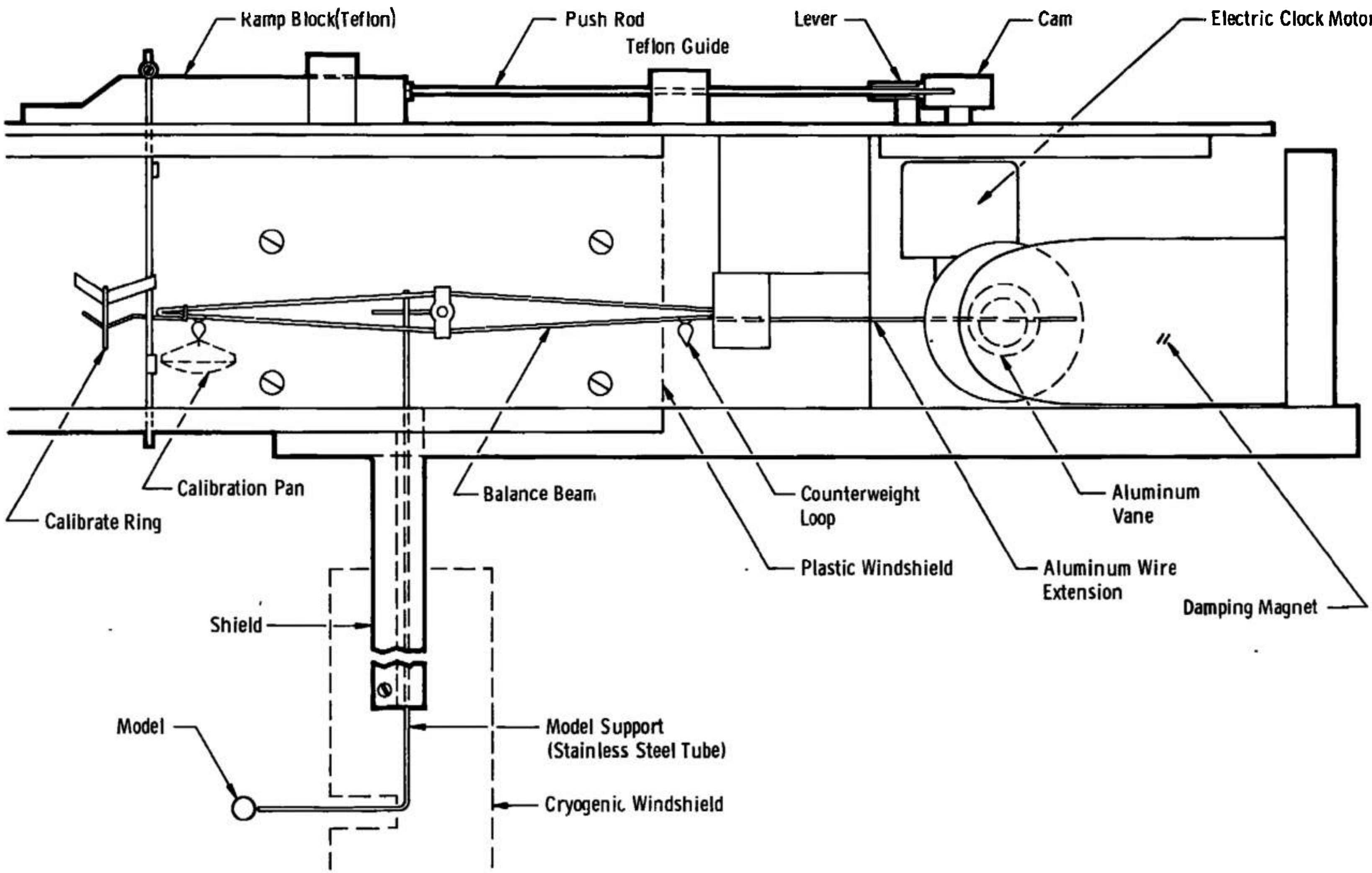


Fig. 4 Drag Balance

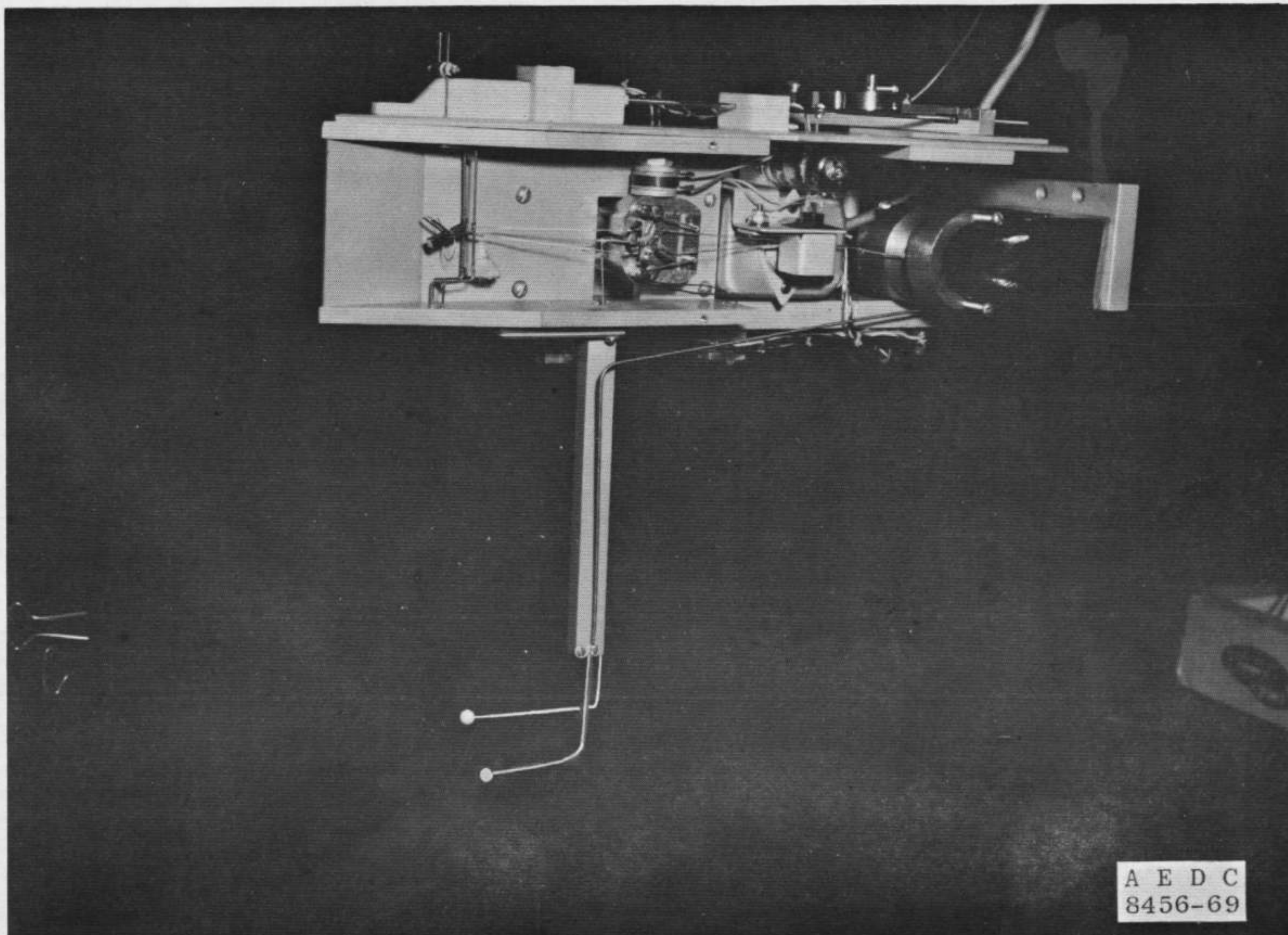


Fig. 5 Photograph of Drag Balance

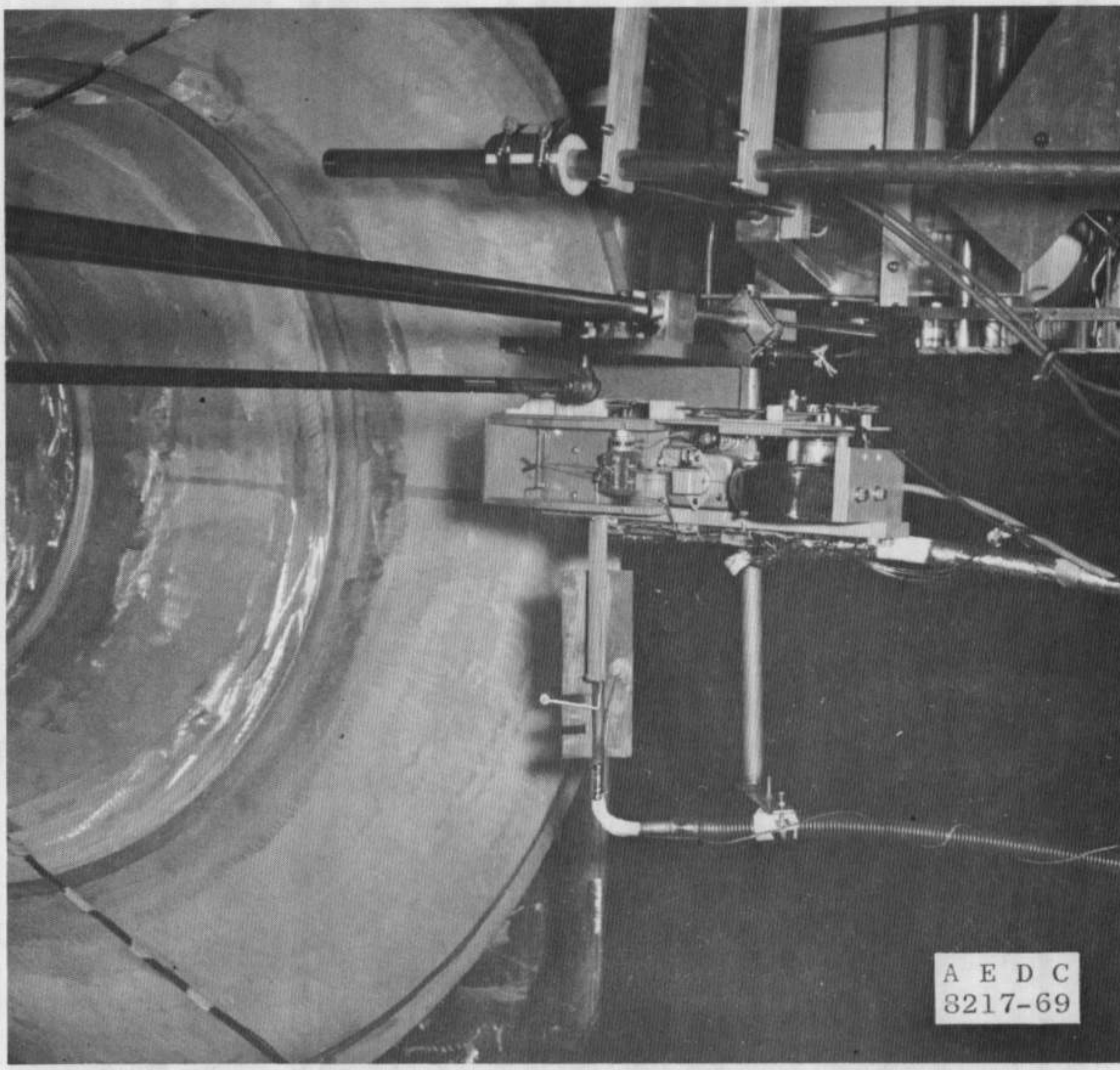
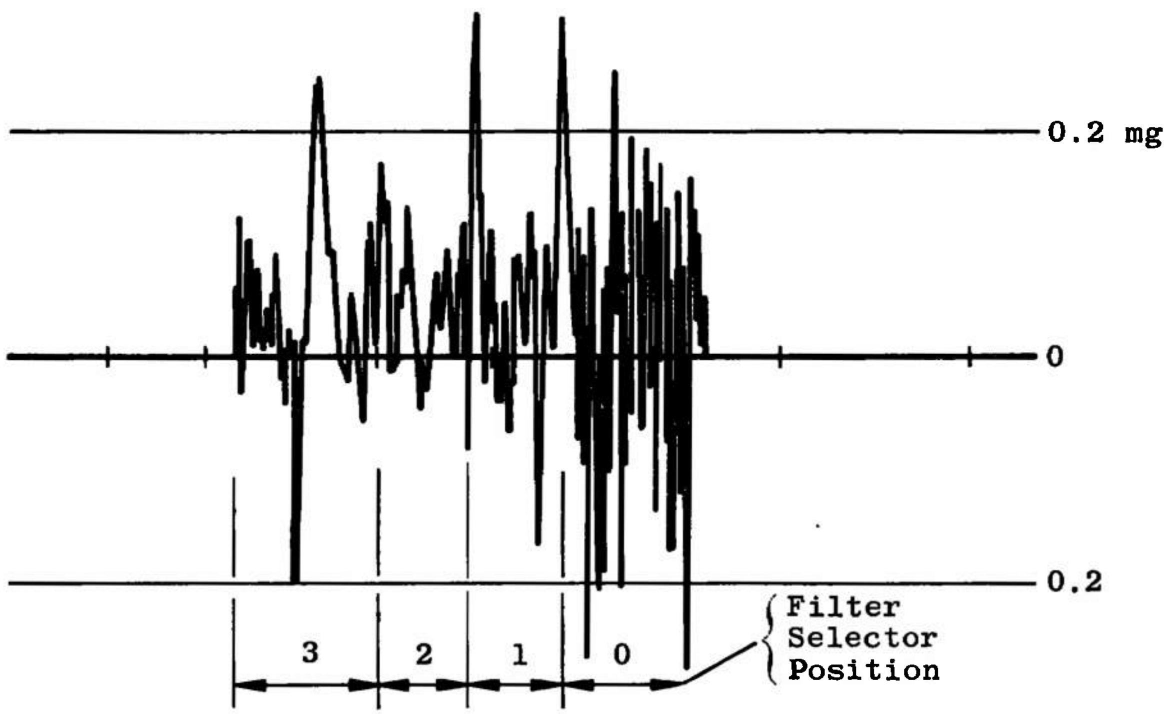
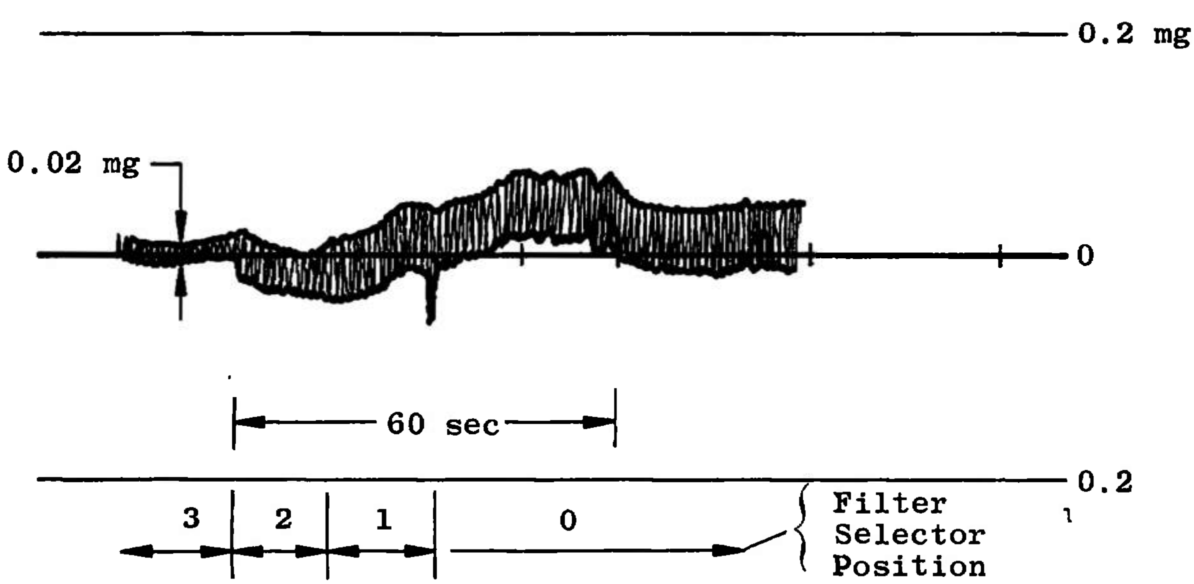


Fig. 6 Installation of Drag Balance in the ARC (8V)



a. Without Magnet



b. With Magnet

Fig. 7 Effect of Eddy Current Damping on Balance Output

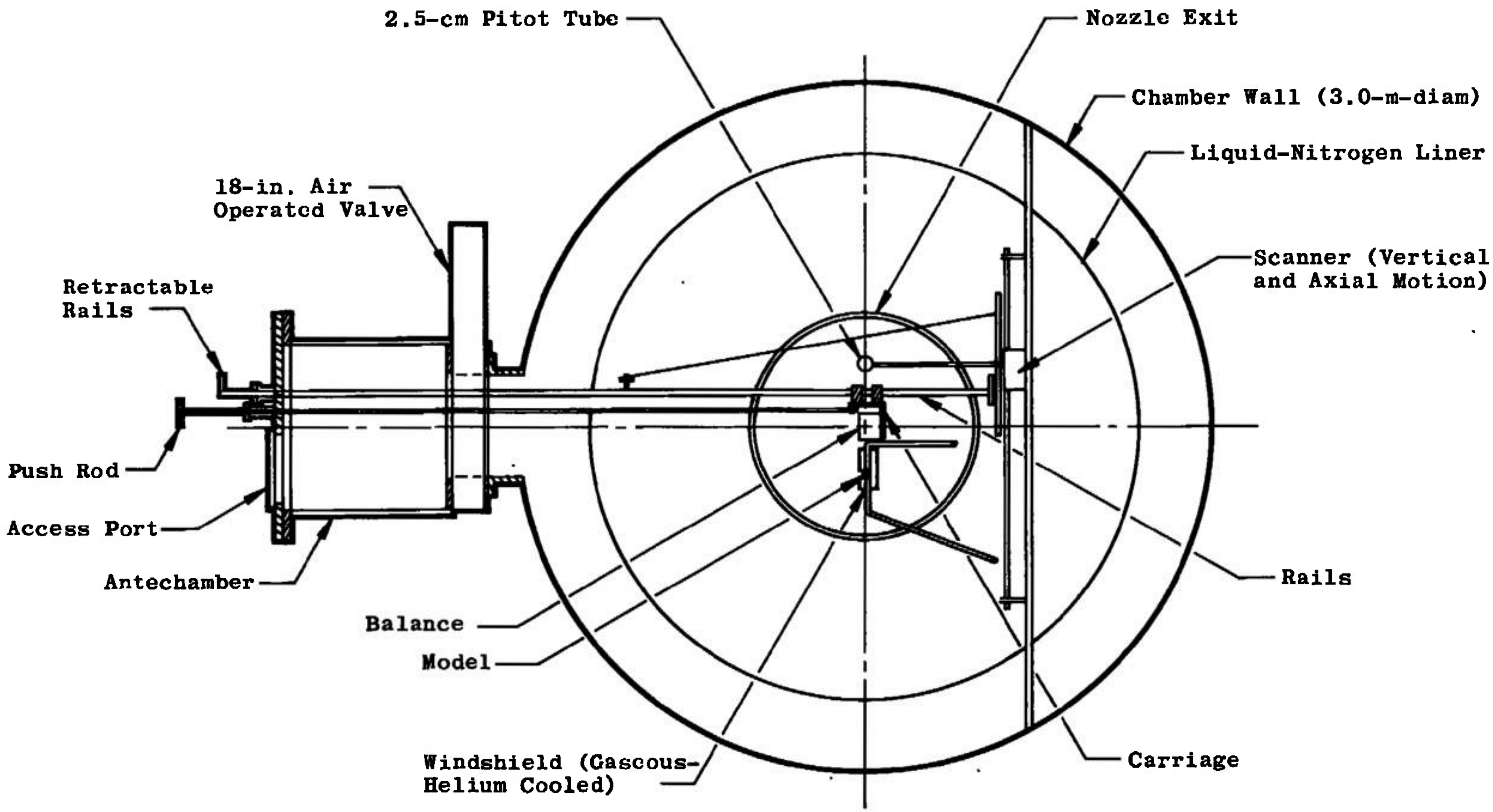


Fig. 8 Installation Schematic, ARC (8V) Section

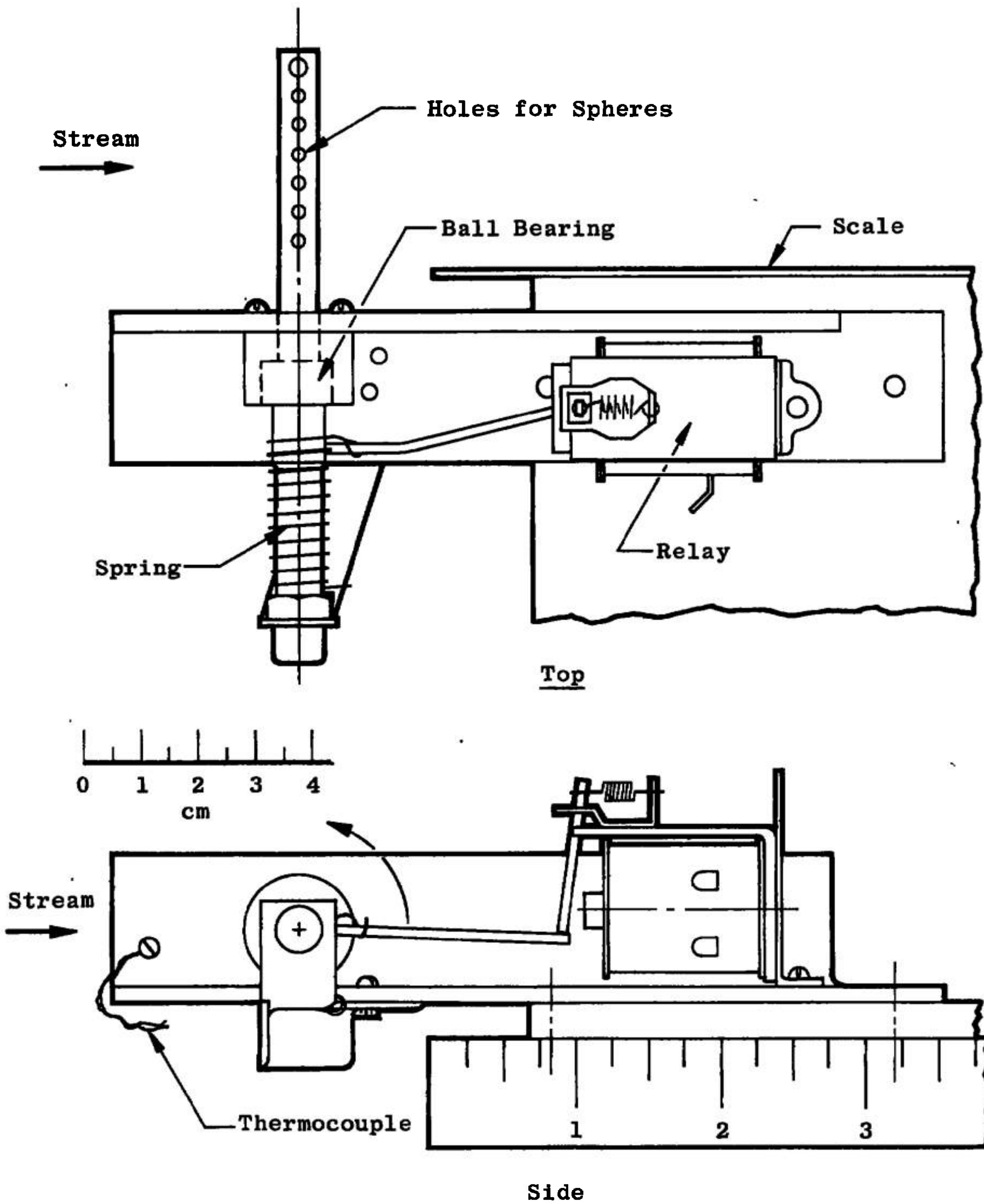


Fig. 9 Sphere Drop Mechanism

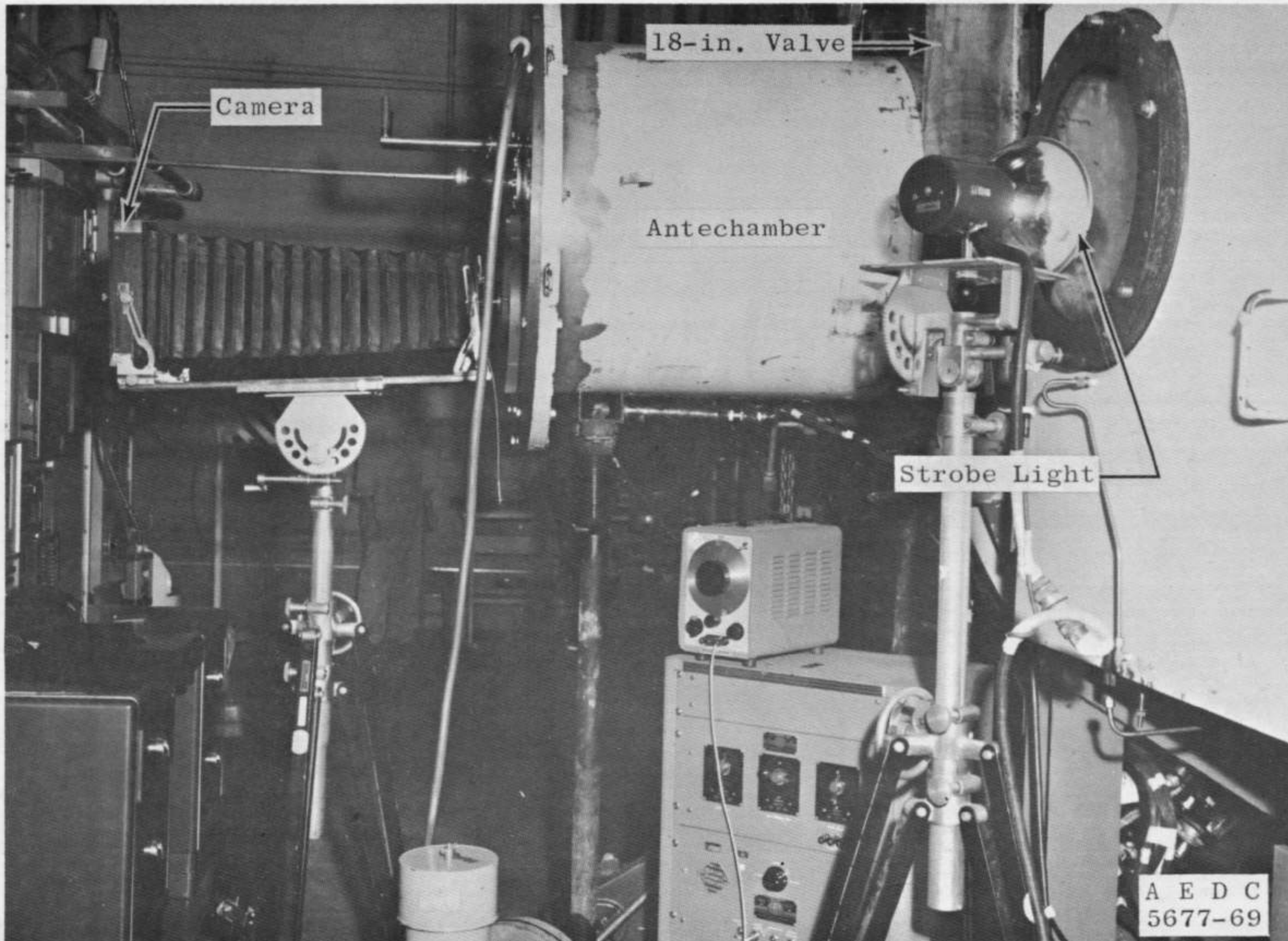


Fig. 10 Antechamber on ARC (8V) and Arrangement for Photographing Freedrop Trajectories

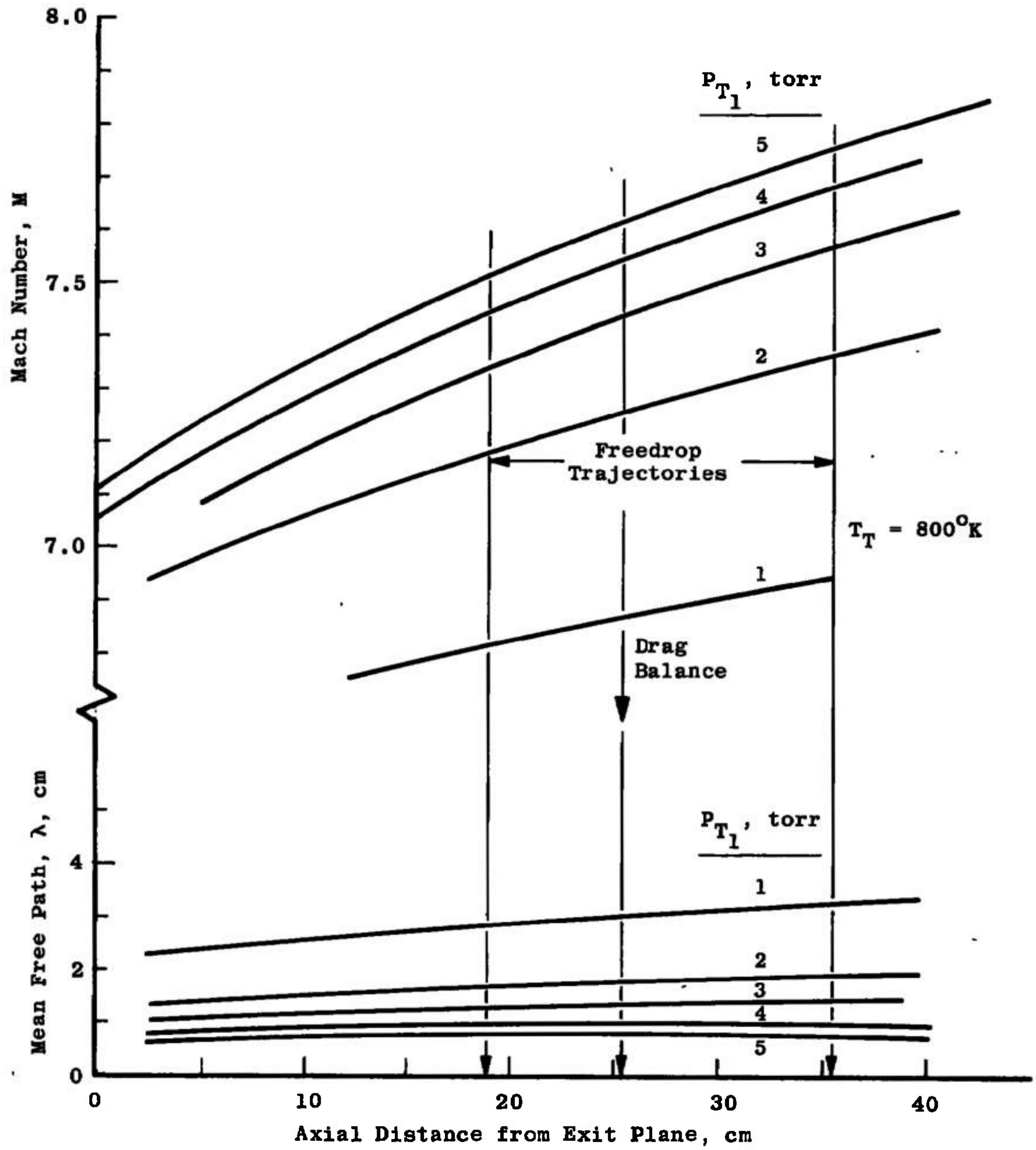


Fig. 11 Nozzle Calibration (M = 6), Mach Number and Mean Free Path on Centerline

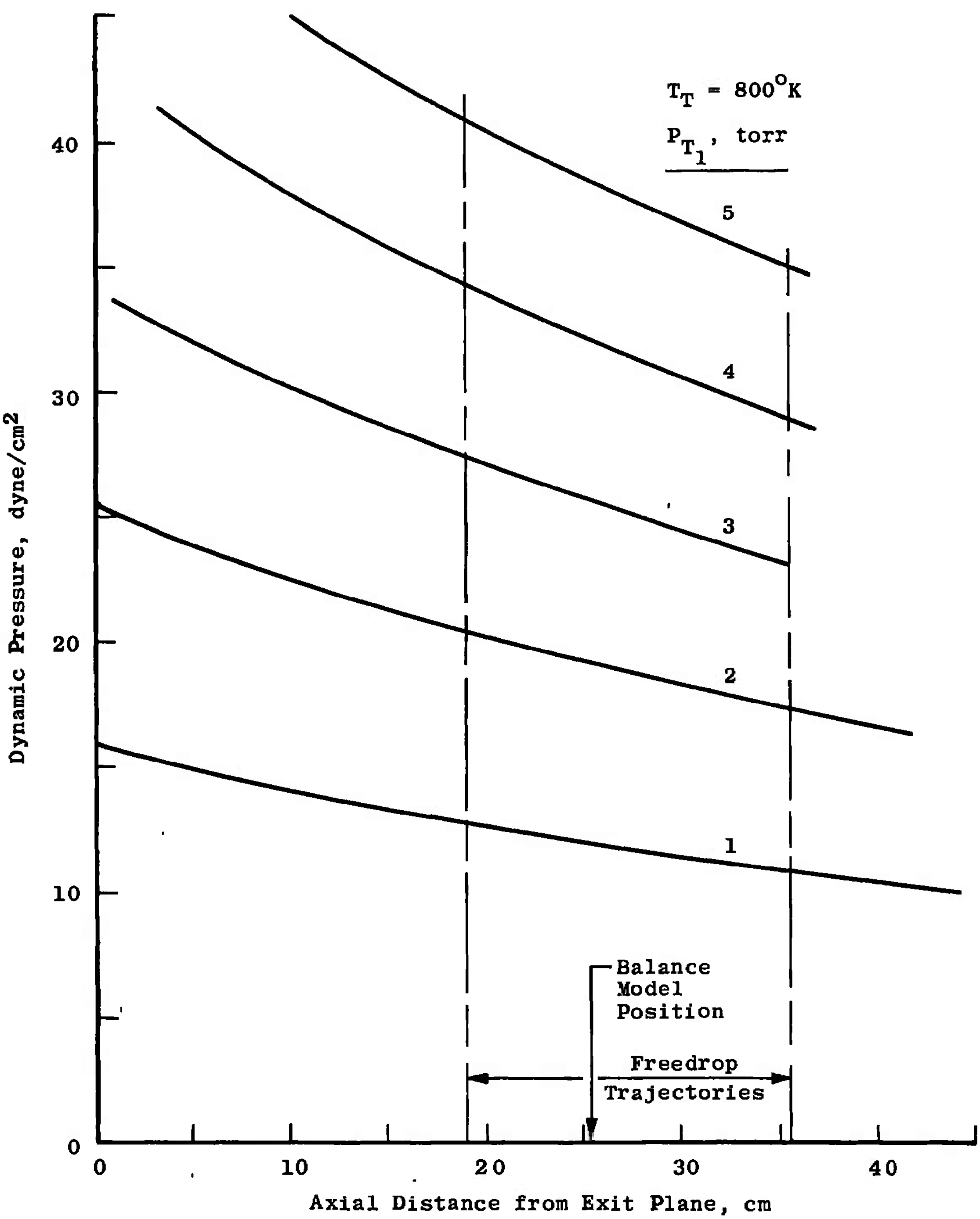


Fig. 12 Dynamic Pressure, M = 6 Nozzle

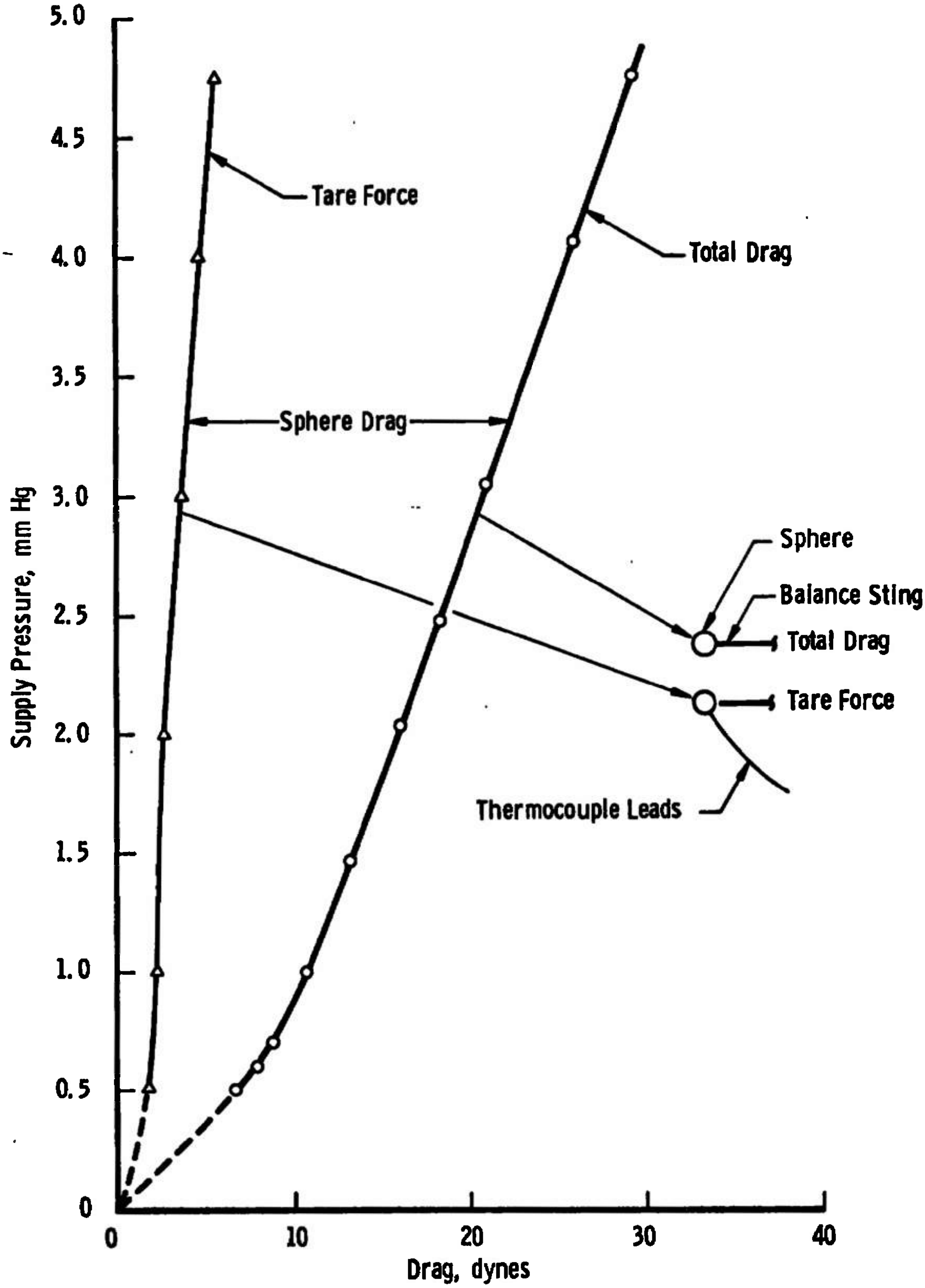


Fig. 13 Drag of Sphere on Balance

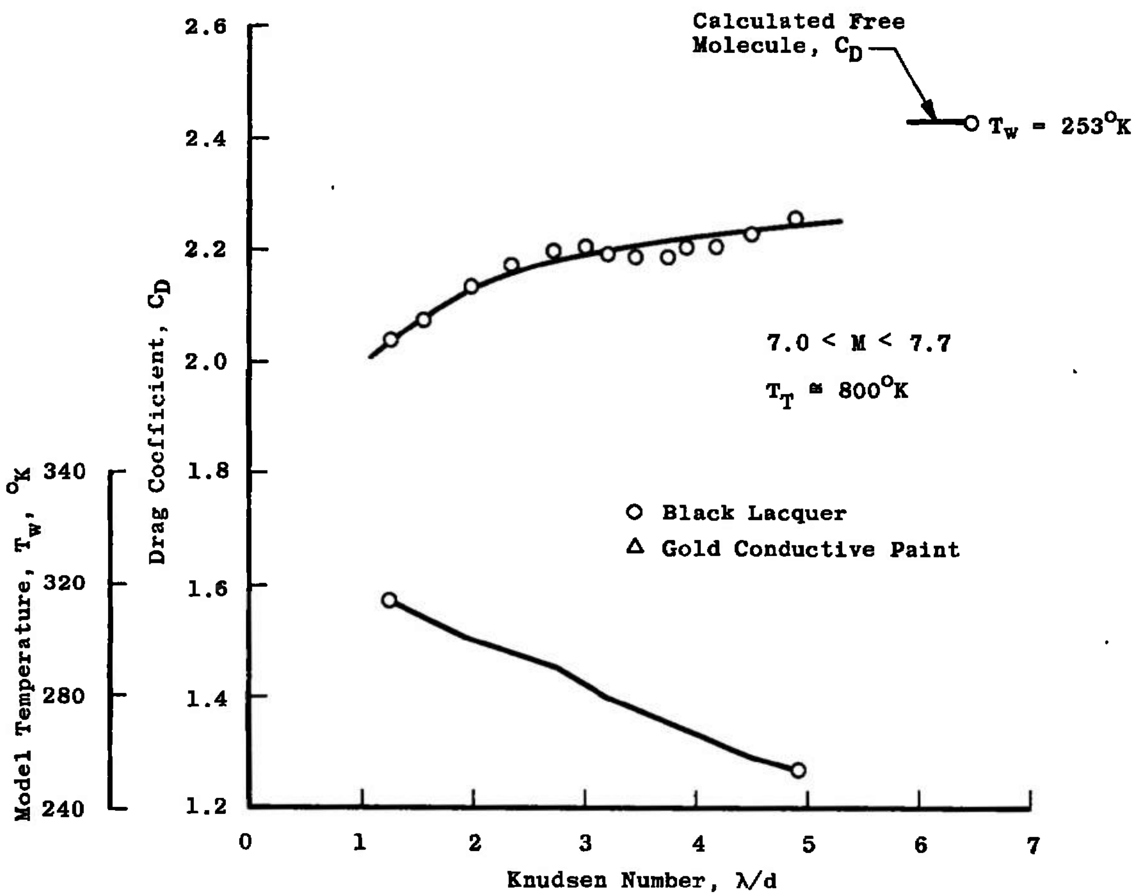


Fig. 14 Drag Coefficient of 6.4-mm Spheres from Balance Data

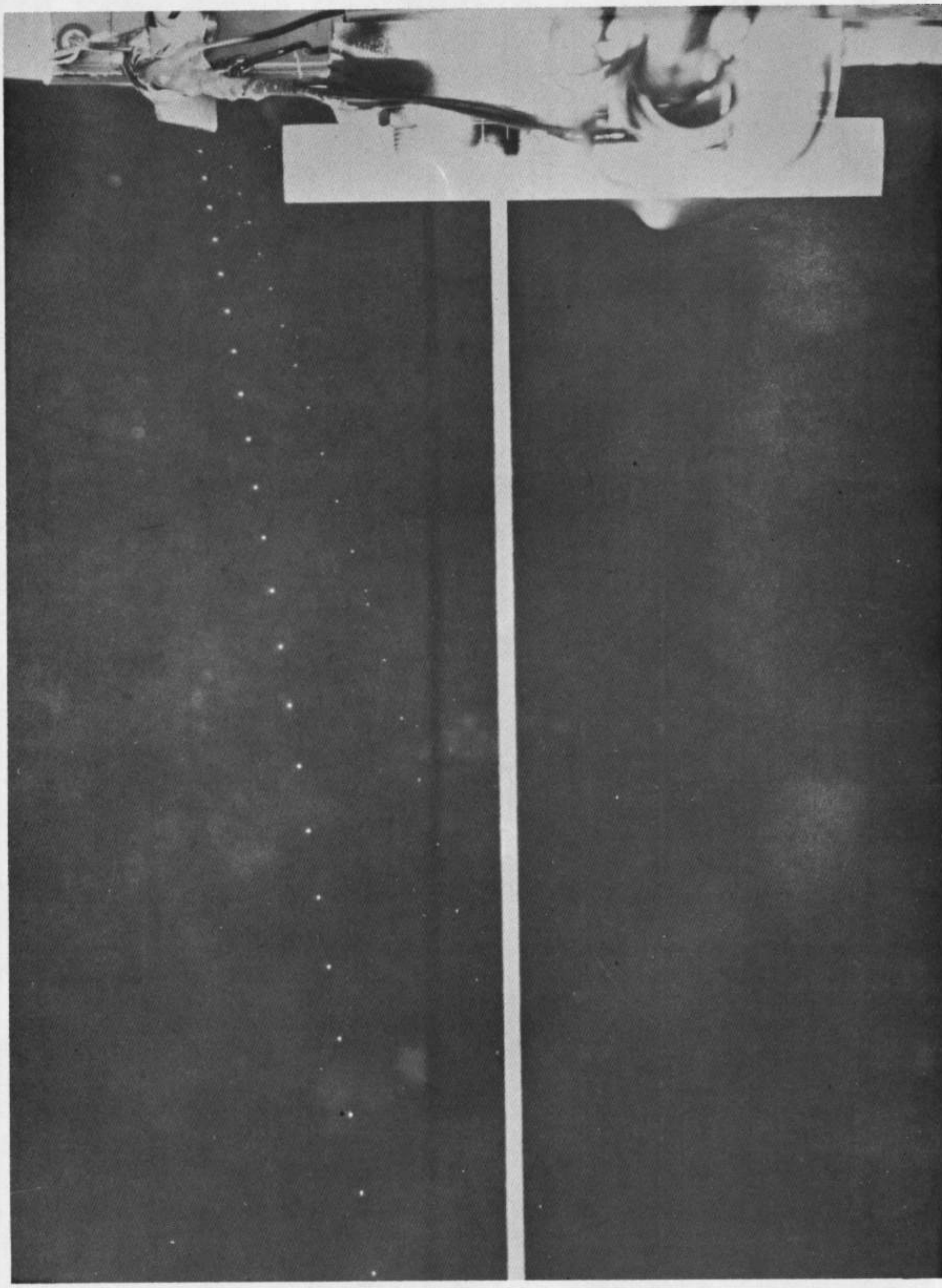


Fig. 15 Stroboscopic Photograph of Freedrop Trajectory

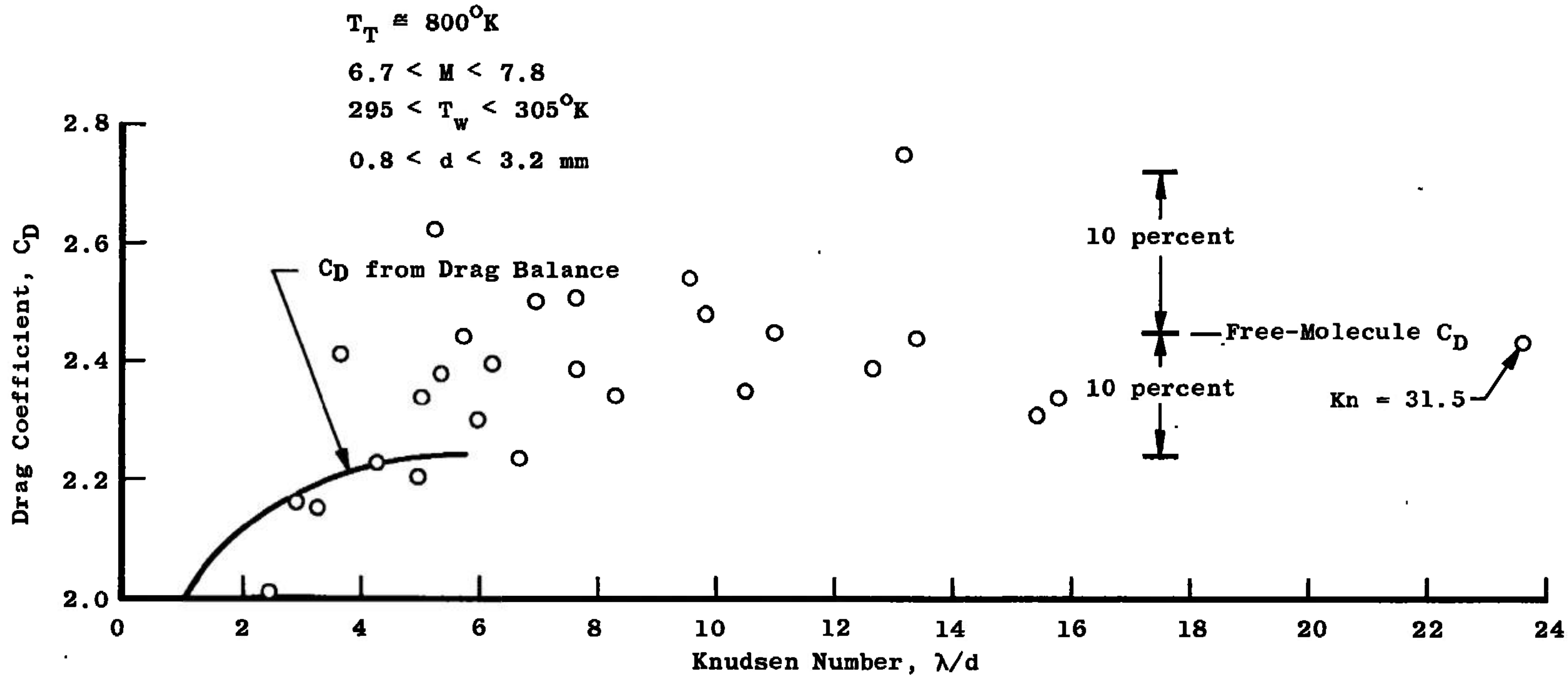


Fig. 16 Drag Coefficient of Spheres from Freedrop Tests

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13. ABSTRACT

Two methods of measuring the drag of bodies in a low density gas stream are described. The supersonic stream had a mean free path as great at 4 cm, and the drag forces were small. A drag balance was adapted from an electrical analytical balance to measure forces up to 70 dynes with less than 1-percent error. With this balance, the drag of spheres was measured for the Knudsen number range from 1.0 to 5. The freedrop trajectory method yielded drag coefficients in the range of Knudsen numbers from 2.5 to 30. These tests demonstrated the feasibility of making accurate drag measurements under the free-molecule conditions that can be generated by exhausting a gas into a cryogenically pumped vacuum chamber.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
aerodynamic drag						
gas flow						
supersonic flow						
Knudsen flow						
free molecule flow						
free fall						
weight indicators						